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WATER-MODERATED NUCLEAR ROCKETS (REVISED)

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Lewis Research Center
Cleveland, Ohio

RESTRICTED DATA
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TECHNICAL MEMORANDUM X-482

WATER-MODERATED NUCLEAR ROCKETS*, **
(Revised)

By Frank E. Rom, Paul G. Johnson, and Robert E. Hyland

SUMMARY

Water-moderated nuclear-rocket powerplants are evaluated to determine the performance capability when used in conjunction with boosters now being developed by the National Aeronautics and Space Administration. The analysis indicates that the resulting powerplants are relatively small and light in weight whether the fuel elements are made of Nichrome, molybdenum, coated graphite, or tungsten-184. Two of the principal design problems - cooling of the water moderator and insulation of the water from adjacent high-temperature fueled regions - are shown to be amenable to known design techniques. Use of tungsten-184 as the fuel-bearing material is expected to yield the highest specific impulse of the materials considered. Tungsten of the required isotopic enrichment can be produced in a portion of the existing Oak Ridge Gaseous Diffusion Plant without modification and without significantly altering the nation's output of enriched uranium.

Performance of orbital-launch nuclear rockets was determined with powerplants utilizing water-moderated reactors and each of the specified fuel-element materials. The nuclear stages were assumed to have been placed in 300-statute-mile (260-Int.-naut.-mile) circular orbits about Earth by Atlas-Centaur or Saturn (C-1, C-2, C-3) boosters. A variety of probe-type missions were assumed for the nuclear stages. For all combinations of booster and mission, the powerplants containing tungsten-184, coated-graphite, or molybdenum fuel elements in water-moderated reactors gave performance several times superior to that expected of the best all-chemical rocket system. Powerplants with Nichrome fuel elements are expected to give performance comparable to that of high-energy chemical

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rockets. When ranked according to estimated vehicle performance, the fuel-element materials assume the same order as the values of specific impulse they are expected to produce; that is, tungsten, graphite, molybdenum, and Nichrome.

INTRODUCTION

Most studies of nuclear-rocket applications have been concerned with manned interplanetary spacecraft (ref. 1) or large boost vehicles. Both applications are expected to occur in the relatively distant future. Early useful application of nuclear rockets requires the development of nuclear upper stages compatible with boost vehicles being developed in the current NASA launch-vehicle program. To be competitive with chemical upper stages, the powerplants used in the nuclear-rocket stages must be relatively light in weight in addition to being capable of producing high specific impulse.

If powerplant weight can be minimized, nuclear rockets can be profitably used in orbital-launch stages boosted by Atlas-Centaur or Saturn (C-1, C-2, C-3) launch vehicles. The corresponding missions would include fast interplanetary instrumented-probe missions that originate from low-altitude Earth orbits. Such missions would be relatively difficult for chemical rockets, so that the higher specific impulse of a nuclear rocket would result in superior performance. Development of such nuclear stages could circumvent the necessity of developing multistage, high-energy chemical space vehicles.

Nuclear-rocket propulsion systems can be made light in weight by the use of hydrogenous moderators. That the superior slowing-down power of hydrogen can be used to produce small reactors is well known. In order for hydrogenous reactors to be also light in weight, the hydrogen-bearing moderator must combine low overall density with high hydrogen concentration. Of all the hydrogenous moderators, only lithium hydride, organic solids or liquids, and water adequately fulfill the dual requirement.

Lithium hydride, if made with natural lithium, has too high a capture cross section for use as a moderator. Therefore, the isotope lithium-7 must be used. Lithium-7 has been produced in quantity and is available in the required enrichment (ref. 2). However, the mechanical properties of lithium hydride are not attractive. The material is brittle and has a high coefficient of expansion, low tensile strength, and poor thermal conductivity (ref. 3). Unless very complicated cooling systems and ingenious methods for reinforcing and strengthening are developed, lithium hydride would be suitable only for reactors of very low power density. The internal heat-generation rates must be small enough that the required cooling does not produce excessive thermal stresses.

Organic solids may be used as lightweight moderating materials, but their low conductivities produce difficult cooling problems unless reactor power densities are low. In addition, radiation damage will limit the useful life of organics. Organic liquids overcome the difficulties of cooling solid moderators in the core, since liquids may be circulated out of the core to be cooled in a heat exchanger. However, the radiation damage problem still exists with organic liquids and may lead to such difficulties as deposits on heat-transfer surfaces or changes in physical properties that affect heat-transfer and flow characteristics.

Liquid water, like a liquid organic, has the virtue that thermal stress is of no concern. The fluid can be circulated out of the core region for removal of the heat picked up therein by both internal generation and direct transfer. Water has an advantage over organics in that radiation damage is not a problem. On the other hand, the narrow temperature range between freezing and boiling imposes stringent requirements on the moderator cooling and circulation system. In the nuclear rocket, the water serves only as moderator. As a result, the power density can be increased by a factor of more than 10 over reactors employing water as a coolant and moderator (moderators absorb less than 10 percent of total reactor power). A power density of about 600 megawatts per cubic foot of core volume would result. The water is not expected, therefore, to be a power-density limit in water-moderated reactors.

The object of this report is to evaluate a nuclear-rocket propulsion-system concept that can be made light in weight and therefore can find early space-flight application. Performance comparisons are made to indicate the advantage of nuclear powerplants over chemical systems for early missions utilizing boosters now being developed or planned in the NASA launch-vehicle program. The water-moderated nuclear-rocket propulsion system is studied first from the point of view of powerplant weight and then on the basis of residual-load performance as a powerplant for nuclear orbital-launch stages. Minimum weights are found for reactors utilizing tungsten-184 as the fuel-element material. Weight estimates are also made for reactors using molybdenum and Nichrome as fuel elements. The weights of powerplants incorporating these reactors are computed by making appropriate allowances for pressure shells, nozzles, turbopumps, heat exchangers, and control systems. The thrust expected from these propulsion systems is determined for a range of reactor operating conditions. The resulting parametric variation of powerplant weight and thrust is used to determine orbital-launch flight performance. Atlas-Centaur, Saturn C-1, Saturn C-2, and Saturn C-3 are assumed to be available as boost vehicles to place the nuclear stages into low-altitude orbits about the Earth. The residual-load performance of the nuclear rocket is obtained for several missions utilizing each of the three boosters. Optimum thrust level is found for each booster-mission combination.

DESCRIPTION OF POWERPLANT

The nuclear-rocket powerplant is composed of (1) a water-moderated, water-reflected reactor, (2) a water-circulating system, (3) a heat exchanger to cool the moderator, (4) a pressure shell to house the reactor, (5) a nozzle, (6) a hydrogen turbopump unit, and (7) a reactor control system. A schematic drawing of a possible powerplant configuration is shown in figure 1. Many features of the core arrangement are similar to the HTRE-1 reactor (ref. 4).

The reactor core is essentially an aluminum tank filled with water and pierced with a number of hexagonal aluminum tubes. The fuel elements inside the tubes consist of hexagonal arrays of flat metallic plates, as shown schematically in figure 2. Insulation between the fuel-element region and the water moderator is provided by shingle-type thermal radiation shields, as illustrated by the inset in figure 2 and described in reference 5, although other techniques are possible. Although the schematic drawing (fig. 1) shows a 19-fuel-element reactor core, smaller or larger reactors for lower or higher powers could contain smaller or larger numbers of fuel elements. Each particular power level for any of the fuel-element configurations would require a particular fuel-element diameter to match the flow-area requirements.

The propellant and moderator flow configurations are shown schematically in figure 3. High-pressure hydrogen from the liquid-hydrogen pump is supplied to the nozzle for regenerative cooling. The hydrogen is then ducted to the folded tube-and-shell heat exchanger, which serves to cool the moderator. The hydrogen enters the tubes of the heat exchanger at the cold end of the reactor, travels the length of the core, and then returns to the cold end where it is discharged into the plenum immediately forward of the fuel-element passages. The hydrogen then passes through the fuel elements. The hot hydrogen from the reactor exit is expanded through the nozzle to produce thrust. A small amount of hot hydrogen for the turbopump drive (not shown in fig. 3) is bled from the exhaust nozzle and mixed with cold hydrogen from the nozzle-cooling-passage exit plenum to achieve the desired temperature. The bleed flow is then ducted to the turbine sections of the hydrogen and water turbopump units. The exhaust from the turbopump units is available for vehicle attitude control.

The cold moderator water circulated by the turbine-driven water pump enters a plenum at the cold end of the reactor. The water is then led to the hot end of the reactor tank by means of a multiple array of tubes. The direction of water flow is reversed at the hot end of the reactor where it is divided into two parallel flows. One portion of the water flows in gaps between the baffles and the aluminum fuel-element tubes, removing the heat transferred through the insulation from the hydrogen side of the aluminum tubes. The remainder of the water flows outside the baffles to remove the heat generated by the neutron and gamma radiations in the main body of the water moderator. At the cold end of the reactor the water enters the shell side of the annular heat-exchanger sections. The water is cooled in the folded counterflow heat exchanger by the cold hydrogen from the nozzle cooling passages. The water in the heat exchanger also serves as part of the reflector. After flowing twice the length of the reactor in the heat exchanger, the moderator water flows to the pump inlet, completing its circuit.

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In the illustrated configuration, control is accomplished by means of rotatable control drums located in the reflector region. (Other schemes such as liquid or gaseous poison systems could be used if required.) The drums are pneumatically actuated by the use of a high-pressure gas supply system.

POWERPLANT WEIGHT AND THRUST ANALYSIS

The powerplant weight and thrust analysis has as its objective the determination of minimum powerplant weights in a specified range of thrust. Physical restrictions on fuel-element dynamic head and the weight of tungsten per unit void cross-sectional area must be taken into account, and reactor-exit pressure must be selected with consideration given to overall mission performance. Methods for determining (1) the weights of the reactor and other powerplant components and (2) the powerplant thrust are presented in this section. The resulting values of powerplant weight and thrust are presented in the RESULTS AND DISCUSSION section.

Reactor Weight

The reactor weights and diameters used in the analysis are given in figure 4. They are partial results of a study now in progress at the NASA Lewis Research Center. The figure gives the minimum weight of bare, water-moderated reactors using tungsten-184 fuel elements as a function of reactor void cross-sectional area, determined by criticality requirements.

The following lethargy-dependent diffusion equations were used to determine the static criticality factor k_{eff} (symbols defined in appendix A):

$$\left[D(u)B_g^2 + \Sigma_a(u) + \Sigma_{in}(u)\right]\varphi(u) + \frac{dQ(u)}{du} = S(u) + \int du'\Sigma_{in}(u')\varphi(u')h(u' \rightarrow u) \tag{1}$$

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$$\gamma(u)\,\frac{dQ(u)}{du} + Q(u) = \xi(u)\Sigma_{es}(u)\varphi(u) \qquad (2)$$

The following assumptions and conditions were assigned in computing the reactor sizes by the use of equations (1) and (2):

(a) The reactor is a bare right circular cylinder.

(b) The reactor composition is completely homogeneous.

(c) The source function is a normalized uranium-235 fission spectrum.

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(d) The volume fraction of uranium dioxide expressed as a fraction of the total tungsten and uranium dioxide volume is 0.15.

(e) The enrichment (abundance) of tungsten-184 is 0.78, which represents the best product reasonably attainable from use of a portion of the Oak Ridge Gaseous Diffusion Plant (see appendix B).

(f) The total weight of tungsten per unit void cross-sectional area is 800 pounds per square foot. This corresponds to a fuel-plate thickness of 0.017 inch, a tungsten structure and insulation allowance of 13 percent of the total tungsten volume, a ratio of total void to flow area of 1.20, and a ratio of heat-transfer length to hydraulic diameter of 300.

(g) The reactor static criticality factor k_{eff} is 1.05 to allow for anticipated negative reactivity effects.

Minimum reactor weights were determined by computing reactor diameters for many combinations of void fraction and length and then graphically optimizing weight as a function of void area. For each combination of void fraction and reactor length, several diameters were assigned to determine the value corresponding to a k_{eff} of 1.05. After computing reactor weight and void cross-sectional area from the known geometry and composition, curves of weight against void area were plotted for the several void fractions. The envelope of these curves defines the minimum reactor weight for each void area and is shown in figure 4. The broken portion of the curves is an extrapolation to very low void areas. The weights shown in this region are approximate, and a uranium concentration greater than 0.15 might be required to satisfy the various reactor assumptions.

The reactor weights can be seen to vary from about 400 pounds for a void cross-sectional area of 0.1 square foot to about 2600 for a void cross-sectional area of 2.5 square feet. The corresponding reactor diameters vary from about 2 to 3 feet. The reactor length-to-diameter ratio for minimum weight was found to be very nearly 0.8 for the range

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of cross-sectional areas shown. The variation of weight with void cross-sectional area is observed to be very close to linear in the range illustrated.

For the purpose of computing weights of powerplants using water-reflected reactors, as illustrated in figure 1, the reactor weights and diameters were assumed to be equivalent to those of bare reactors of the same void cross-sectional area. For thin reflectors surrounding a core with voids, the overall diameters of reflected reactors may be slightly less than those of bare reactors. The effect on weight would be expected to be small, since the amount of tungsten, which is a major weight component, is by definition the same for reactors of the same void cross-sectional area. The changes in reactor overall diameter caused by the addition of a reflector would affect only the water volume, which would not be greatly affected when the reflector is thin.

The weights of reactors using molybdenum and Nichrome as fuel elements are calculated by assuming that these materials occupy the same volume as the tungsten-184 that is replaced. The effect on reactivity of the interchange of materials is expected to be slight, since the cross sections for all these materials are low and are fairly close to each other. The weights of water-moderated reactors with niobium-carbide-coated graphite fuel elements were determined by direct calculation for selected conditions. The assumed fuel concentration was 300 milligrams of uranium dioxide per cubic centimeter of graphite. The coating was accounted for by including niobium in the amount of 15 percent of graphite weight.

Calculations were made to determine the effect of uranium dioxide concentration and tungsten-184 enrichment on minimum reactor weight. The results are presented in figure 5. The solid line shows the reference case of 0.15 uranium dioxide concentration and 0.78 tungsten-184 enrichment. The effect of doubling the uranium dioxide concentration is shown by the circled point. A curve for this condition would be nearly identical to the solid line. Very little change results in the reactor weight as a function of void area, indicating that highly loaded fuel elements are not required. In addition, the fuel burnup will be small, less than 1.0 percent.

The dash-dot line indicates the effect of increasing the tungsten-184 enrichment to 1.00. The comparison indicates that about a 10-percent increase in weight occurs by use of 0.78 tungsten-184 enrichment instead of 1.00 enrichment. The dashed line shows the case for the lowest of the three tungsten-184 enrichments considered (see appendix B). The penalty in reactor weight is about 30 percent when compared to the 1.00 tungsten-184 enrichment. Figure 5 indicates that the best product that can be reasonably attained is more than an adequate enrichment for water-moderated tungsten-184 reactors.

Thrust

The reactor thrust is found by multiplying the mass flow of hydrogen by the specific impulse in vacuum:

$$F = wI_{vac} \tag{3}$$

where the reactor mass-flow rate w is given by

$$w = \rho V A_f \tag{4}$$

which can be expressed as a function of reactor-exit Mach number, reactor-exit total temperature, and reactor-exit total pressure by

$$w = \frac{A_f P_e M_e \sqrt{\frac{\gamma g}{RT_e}}}{\left(1 + \frac{\gamma - 1}{2} M_e^2\right)^{(\gamma+1)/2(\gamma-1)}} \tag{5}$$

The void cross-sectional area is assumed to be 20 percent greater than the fuel-element flow area A_f to account for insulation void area. Since the dynamic head q is given by

$$q_e = \frac{\rho_e V_e^2}{2g} = \frac{\gamma p_e M_e^2}{2} \tag{6}$$

the Mach number corresponding to any assigned dynamic head is given by

$$M_e = \sqrt{\frac{2q_e}{\gamma p_e}} \tag{7}$$

where

$$p_e = \frac{P_e}{\left(1 + \frac{\gamma - 1}{2} M_e^2\right)^{\gamma/(\gamma-1)}} \tag{8}$$

Thus, by assigning the reactor-exit total pressure, total temperature, and dynamic head, the mass flow for any given exit flow area can be determined from equation (5). Physical properties of hydrogen are found in reference 6. Hereafter, all temperatures and pressures are total values unless otherwise specified.

The following table lists the vacuum specific impulse values used in the analysis, which were obtained from reference 7 for a nozzle area ratio of 50 and a velocity correction factor of 0.96. Melting points for the fuel-element materials and corresponding anticipated gas temperatures are also shown:

Fuel-element material	Nichrome	Molybdenum		Tungsten	
Material melting temperature, °F	2550	4760		6170	
Reactor-exit hydrogen temperature, °F	1500	3000	3500	4000	4500
Specific impulse in vacuum, lb/(lb/sec)	526	713	769	826	886

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Data obtained at the Lewis Research Center of the NASA (refs. 8 and 9) indicate considerable promise for the use of sintered tungsten - uranium dioxide composites as nuclear-rocket fuel elements. The first composites produced contained 20 percent by volume uranium dioxide, were 0.030 inch thick, and included 3-mil cladding on each surface but no cladding on the edges. The tests performed on these specimens indicated a loss of uranium dioxide of less than 4 percent while maintaining a temperature of 4750° F for 1 hour in vacuum. This work led to the assumption that tungsten fuel elements will operate at a temperature of 4500° to 5000° F, since the overall UO_2 concentration of 0.15 corresponds to about 0.20 concentration in the fuel elements. Heat-transfer analyses indicate that gas temperatures within 500° F of maximum fuel-element temperature can be achieved. The calculations take into account estimated power distributions, thermal radiation between surfaces, hydrogen dissociation and property variations, and flow in parallel passages.

Molybdenum fuel elements are expected to be capable of operation at 3500° to 4000° F. Corresponding hydrogen temperatures would be 3000° to 3500° F. Nichrome can be operated at temperatures of about 1800° to 1900° F, as demonstrated by tests of the HTRE-1 (ref. 4), with a hydrogen temperature of 1500° F being a reasonable expectation. In later comparisons with graphite-fuel-element powerplants the assumption is made that niobium-carbide-coated graphite fuel elements can operate for the required propulsion times up to a maximum temperature of 2500° C (4532° F) (ref. 10). Corresponding gas temperatures of 3500° to 4000° F are specified.

In all calculations, the reactor-exit pressure is chosen to be 300 pounds per square inch absolute. The selection is based on reference 11, which indicates that this is a near-optimum pressure for orbital-launch applications of nuclear rockets.

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In the absence of experimental data on tungsten fuel elements, the value of dynamic head to be used is quite arbitrary. The dynamic head that results in fuel-element failure is a function of variables such as (1) operating temperature, (2) geometrical arrangement, (3) strength of the material, and (4) fabrication technique. In order to reduce the number of parameters to be investigated, a value of 10 pounds per square inch is used for the dynamic head unless otherwise noted.

Propulsion-System-Component Weights

The propulsion-system components, defined as all items except the reactor, include the pressure shell, nozzle, hydrogen turbopump, heat exchanger, water pump, and reactor control system. The weights of the pressure shell, nozzle, and hydrogen turbopump are computed from the relations given in reference 11. The pressure shell is aluminum with a design stress of 20,000 pounds per square inch. The stainless-steel nozzle is designed for an operating stress of 60,000 pounds per square inch. Reference 12 indicates that regenerative cooling is possible with a throat wall temperature of about 2000° R. The hydrogen turbopump is assigned a minimum weight of 40 pounds.

Preliminary designs of water-to-hydrogen heat exchangers indicate that a good approximation to the heat-exchanger weight is given by

$$W_{hx} = 0.25\ Q \tag{9}$$

where Q is the reactor power in megawatts. The weight of the heat exchanger is in pounds and includes the water contained within it. An analysis of a typical heat exchanger is given in appendix C. The calculation is based on a total heat-input rate to the water of 7 percent of reactor power. Of the 7 percent, only about 0.4 percent would be transferred through the shingle-type thermal insulation, as computed in appendix D. The shingle insulation assumed has an overall thickness of 0.072 inch and is made up of 0.002-inch tungsten strips. Other insulation schemes are possible and would probably result in comparable heat fluxes and weights. The weight of water pump and drive is given by

$$W_{wp} = 0.10\ Q \tag{10}$$

A minimum value of 40 pounds is assumed for the water-pump unit. For the assumed constant values of pressure and dynamic head, the weight of the reactor control system is given by

$$W_{cs} = 63 + 0.038\ Q \tag{11}$$

[redacted]

A minimum value of 100 pounds is assumed for the control system. Equations (9), (10), and (11) are applicable only in the reactor power range of this study. Although these component weights are crude estimates, the results of the study are very insensitive to large changes in the assumptions. Consequently, explicit inclusion of other items such as piping, valves, and miscellaneous structure would not alter the conclusions.

MISSION PERFORMANCE

The performance of the water-moderated nuclear-propulsion system is calculated assuming that the nuclear stages are launched from 300-statute-mile (260-Int.-naut.-mile) circular orbits about Earth. The nuclear stages are assumed to be placed in orbit by chemical vehicles now under development or being planned by the NASA. The missions for the orbital-launch nuclear stages are listed in the following table, along with the four boost vehicles considered. Mission-booster combinations are selected so as to cover the range of performance capability inherent in each nuclear-stage gross weight. The booster payloads listed are for orbit altitudes of approximately 300 statute miles:

Mission	Velocity increment, Δv, miles/sec	Boost vehicle (payload, lb)
Escape	1.96	Atlas-Centaur (8000)
75-Day Venus probe	2.55	Atlas-Centaur, Saturn C-1 (19,000), Saturn C-2 (45,000)
100-Day Mars probe	3.60	Atlas-Centaur, Saturn C-1, Saturn C-2, Saturn C-3
413-Day Jupiter probe	5.27	Saturn C-1, Saturn C-2, Saturn C-3 (81,000)
125-Day trip to Mars orbit	7.38	Saturn C-3

The characteristics of the specified missions are described more fully in reference 7.

Boost Vehicles

The boost vehicles used to place the nuclear stages in orbit are the Atlas-Centaur, Saturn C-1, Saturn C-2, and Saturn C-3, as described in reference 13. The Atlas-Centaur is in the final phases of development and is expected to be capable of placing approximately 8000 pounds in a

300-statute-mile orbit. In computing the performance of the nuclear stage, the assumption is made that the transition structure required between the final chemical stage and the nuclear stage weighs 5 percent of the booster payload. The transition structure is left in orbit, making the initial weight of the nuclear stage 7600 pounds.

The three models of the Saturn booster represent development phases starting with the earliest version and extending to the highest-performance version currently envisioned. The Saturn C-1 is under development by the NASA and is expected to be capable of placing 19,000 pounds in a 300-statute-mile orbit about the Earth. The Saturn C-2 uses a new second stage and should have a payload of about 45,000 pounds for the same mission. Corresponding nuclear-stage weights are assumed to be 18,000 and 42,700 pounds, respectively. The Saturn C-3 is in the planning stage at present and represents the ultimate to be expected from the Saturn program through uprating of the propulsion systems of the various stages. For a payload of 81,000 pounds, the initial nuclear-stage weight is assumed to be 77,000 pounds.

Nuclear Stage

The nuclear stage is composed of the water-moderated nuclear powerplant, liquid-hydrogen propellant tankage, propellant, vehicle structure, and residual load. Weights of tank, propellant, and structure are accounted for by using the charts of residual-load plus powerplant weight in reference 7. The pressure-stabilized tanks are assumed to be fabricated of aluminum and weigh approximately 3.5 to 5 percent of the propellant weight, depending on the size of the tank. Powered trajectory calculations are used in reference 7 to determine the propellant requirements as functions of initial thrust, gross weight in orbit, and specific impulse for each of the desired missions. The nuclear-stage structure is assumed to be 4.5 to 7.5 percent of the initial nuclear-vehicle weight, depending upon chemical-stage diameter. This structure represents the supports necessary between the powerplant and the tank, supports for guidance and vehicle control systems, and supports and fairings for the payload.

The residual load consists of all items excluding the powerplant, tankage, propellant, and vehicle structure. Thus, such items as payload, vehicle guidance and control systems, communication equipment, shielding (if required), and electrical power supplies are considered as residual load. Residual-load plus powerplant weights are obtained from reference 7 for each of the mission-booster combinations, for the specific impulses corresponding to each of the reactor fuel-element materials, and for a range of thrust levels. The powerplant weight corresponding to each combination of thrust and reactor material is then subtracted from the residual-load plus powerplant weight to determine the residual load.

RESULTS AND DISCUSSION

The early application of nuclear rockets requires the development of nuclear upper stages that can be utilized in conjunction with the chemical boosters now being developed by the NASA. The nuclear powerplants for these stages must be light in weight to yield performance advantages over high-energy chemical upper stages. Nuclear-rocket powerplants moderated with water are investigated to determine their performance capabilities in conjunction with the Atlas-Centaur and Saturn booster systems.

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Powerplant Performance

The thrust produced by flowing hydrogen through water-moderated reactors may be expressed as a function of flow area, reactor-exit pressure, reactor-exit dynamic head, and nozzle area ratio. The nozzle area ratio is considered fixed at 50:1 for this report. Figure 6 is a plot of reactor weight as a function of thrust level and reactor-exit dynamic head. The reactor-exit total pressure is 300 pounds per square inch absolute, and the dynamic head is varied from 1 to 98 pounds per square inch absolute. Figure 6(b) is an enlargement of the low-thrust portion of figure 6(a). The thrust level can be shown to be independent of reactor-exit total gas temperature for any given flow area, reactor-exit total pressure, and reactor-exit dynamic head if the gas constant and ratio of specific heats remain constant. Thus, figure 6 applies to any temperature up to about 4500° F, where dissociation effects begin to alter the gas properties significantly.

As the dynamic head is varied from 1 to 98 pounds per square inch, corresponding to reactor-exit Mach numbers from 0.07 to 0.87, the thrust increases from 1400 to 11,000 pounds for a reactor weight of 500 pounds. It is quite important, therefore, to use as high a value of dynamic head as possible in order to obtain maximum thrust from a given reactor. Of course, the materials and the design of the fuel elements impose limits on attainable dynamic head. To date, no experience is available with tungsten fuel elements. Clearly, for each desired operating temperature level, there is a dynamic head at which the tungsten fuel elements will fail. For lack of experimental data on tungsten fuel elements, a value of 10 pounds per square inch is arbitrarily chosen as the design dynamic head. At this dynamic head, reactors producing thrusts of 10,000 pounds or less will weigh less than 750 pounds. For a fixed flow area, the reactor thrust level can be shown to be directly proportional to the square root of the product of reactor-exit dynamic head and reactor-exit total pressure. Thus, the thrust level for any desired combination of dynamic head and pressure can be simply determined from figure 6.

Weights of water-moderated tungsten-184 powerplants are shown in figure 7 as a function of thrust and dynamic head for the same reactor operating conditions as in figure 6. Figure 7(b) is an enlargement of the low-thrust portion of figure 7(a). These weights are used in the subsequent mission analysis. Dynamic head is again noted to be of great importance, and a value of 10 pounds per square inch is arbitrarily used for further analysis. A 10,000-pound-thrust powerplant is shown to weigh under 1200 pounds. Table I lists more detailed characteristics and a weight breakdown of three tungsten-184 water-moderated nuclear-rocket powerplants.

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The effect of using molybdenum and Nichrome instead of tungsten-184 as the fuel-element material is shown in figure 8. The powerplant weight is plotted as a function of thrust for a dynamic head of 10 pounds per square inch and a reactor-exit pressure of 300 pounds per square inch absolute. For the tungsten powerplant, the weight of tungsten per unit void cross-sectional area is 800 pounds per square foot. The molybdenum and Nichrome reactors have exactly the same volume of fuel-element material as the tungsten reactor; therefore, the weight of the fuel elements is reduced in proportion to the change in material density involved. Lower powerplant weights result. However, the operating temperatures of the molybdenum and Nichrome fuel elements are also lower, as previously discussed. The water-moderated, graphite-fuel-element powerplant is generally intermediate between tungsten-184 and molybdenum in both weight and gas temperature. At very low thrusts, however, the graphite-and-water reactor is the lightest of the types illustrated.

Mission Performance

The performance of water-moderated nuclear powerplants for various probe-type missions utilizing the boosters now being developed or planned by the NASA is presented as an indication of the potential of these powerplants for early application. Water-moderated powerplants utilizing tungsten-184, molybdenum, and Nichrome as fuel-element materials are compared with both the current nuclear-rocket powerplant designs utilizing graphite for both fuel elements and moderator and a hybrid concept using water moderator and graphite fuel elements.

The missions used for comparison purposes originate from orbits about Earth, on the grounds that such missions may be the earliest achieved. The required thrust levels are an order of magnitude less than those for second-stage applications and two orders of magnitude less than those for first-stage applications. The lower power levels should result in shorter, less complex, and less costly powerplant development programs. The orbital operation technique may prove to be the safest with respect to hazards and international acceptance. Therefore, this mode of operation may suffer the least delay due to such factors.

Atlas-Centaur missions. - The Atlas-Centaur is assumed to be capable of placing a 7600-pound nuclear-rocket space vehicle into a 300-statute-mile Earth orbit. Advanced versions of the Titan may also be capable of the same performance. Figure 9 gives nuclear-stage performance in terms of residual load for escape-probe, 75-day-Venus-probe, and 100-day-Mars-probe missions. Water-moderated powerplants using tungsten-184, molybdenum, and Nichrome fuel-elements are considered. Thrust is varied from 1500 to 5000 pounds to determine the best thrust level, and performance bands are shown for the tungsten and molybdenum systems to illustrate the effect of the assumed gas-temperature ranges.

In spite of the lower powerplant weights resulting from the use of molybdenum and Nichrome, the performance is poorer than that expected with tungsten-184. The higher specific impulse of the tungsten system more than overcomes its higher weight. The near-optimum thrust level for all three missions is about 3000 pounds. As the difficulty of the mission increases, the relative advantage of the tungsten system increases. For the 100-day-Mars-probe mission, the tungsten-184 system is expected to deliver about 20 percent more residual load than the molybdenum system and 150 percent more than the Nichrome systems (see fig. 9(c)). The performance of the Nichrome system with its vacuum specific impulse of 526 is considered to be comparable to a high-energy chemical system after accounting for the higher mass fraction of the nuclear rocket. Therefore, the tungsten powerplant will deliver about 2.5 times the residual load of the best chemical system for the most difficult of the three missions. Even for the two simpler missions, the tungsten system will deliver 50 and 75 percent more residual load than the chemical system.

The all-graphite propulsion system, which is assumed to weigh 8000 pounds, cannot be considered for these missions with the Atlas-Centaur, since the powerplant weight equals the payload the Atlas-Centaur can place in orbit. The water-moderated powerplant with coated-graphite fuel elements is shown to give vehicle performance approximately equal to that of tungsten-184.

Saturn C-1 missions. - The earliest version of the Saturn booster, designated C-1, is assumed to be capable of placing an 18,000-pound nuclear vehicle into a 300-statute-mile Earth orbit. Figure 10 gives the performance expected for the 75-day-Venus-probe, 100-day-Mars-probe, and 413-day-Jupiter-probe missions. The thrust level for the metallic-fuel-element, water-moderated powerplants is varied from 3000 to 10,000 pounds. Optimum thrust is about 8000 pounds, but residual-load capability is not sensitive to deviations from optimum. For the Mars-probe mission (fig. 10(b)), the tungsten-184 system gives about 15 percent more residual load than the molybdenum system and nearly 90 percent more than the Nichrome system. For the most difficult mission the tungsten-184 system shows about a 2.5 residual-load advantage over the Nichrome system, which is comparable to an all-chemical system.

The all-graphite system is assumed to weigh 8000 pounds, produce hydrogen temperatures of 3500° to 4000° F, and operate at a thrust level of 50,000 pounds. With these characteristics it yields a residual load for only one of the assigned C-1 missions, the Venus probe. Figure 10(a) shows the resulting residual load to be less than one-third that of the Nichrome system. Thus, the all-graphite design is concluded to be oversized for a nuclear orbital-launch stage of only 18,000-pound gross weight. The graphite-fuel-element, water-moderated system is shown to yield residual-load values between the bands corresponding to tungsten and molybdenum fuel elements. Only one pair of points is shown for clarity of presentation.

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Saturn C-2 missions. - The Saturn C-2 is assumed to be capable of placing a 42,700-pound nuclear vehicle into a 300-statute-mile Earth orbit. Figure 11 gives the performance expected for the 75-day-Venus-probe, 100-day-Mars-probe, and 413-day-Jupiter-probe missions. The thrust level for the tungsten-184, molybdenum, and Nichrome water-moderated powerplants is varied from 5000 to 25,000 pounds. The effect of thrust level is quite small, as can be judged from the flatness of the curves. A thrust level of 10,000 pounds will give residual loads within 5 percent of the actual optimum shown, which is in the thrust range of 20,000 to 25,000 pounds for all three missions. In the most difficult of the three missions selected, the tungsten-184 system will deliver about 2.5 times the payload of the Nichrome or all-chemical systems and about 25 percent more than the molybdenum system (fig. 11(c)).

The all-graphite system gives about the same performance as the optimum water-moderated Nichrome system. Again, the water-graphite system gives performance between that of the tungsten and molybdenum systems.

Saturn C-3 missions. - The Saturn C-3 is assumed to be capable of placing a 77,000-pound nuclear vehicle into a 300-statute-mile orbit about Earth. Figure 12 gives the performance expected for the 100-day-Mars-probe, 413-day-Jupiter-probe, and 125-days-to-Mars-orbit missions. The thrust level is varied from 15,000 to 50,000 pounds. A thrust level of 30,000 pounds gives optimum or near-optimum performance for all three missions. The tungsten system appears capable of placing 6.5 to 7.5 times as much residual load into an orbit about Mars as will the Nichrome or all-chemical systems, about 30 to 45 percent more than the molybdenum system, about 2.5 to 3 times as much as the all-graphite system, and about 15 to 20 percent more than the water-graphite system (fig. 12(c)). For the two less-ambitious missions, the performance gains possible with the water-moderated system are not quite as striking but are nevertheless substantial.

[redacted]

With the Saturn C-3, the molybdenum-fuel-element, water-moderated system delivers about 15, 25, and 90 percent more residual load than the all-graphite system for the three missions in order of increasing difficulty.

SUMMARY OF RESULTS

Water-moderated nuclear-rocket powerplants have been studied to determine their capability in orbital-launch nuclear stages. Stage weights corresponding to boosters now being developed or planned by the NASA are considered. The following values are assumed for reactor-exit hydrogen conditions for the various fuel-element materials considered:

Total pressure, P_e, lb/sq in. abs	300
Dynamic head, q_e, lb/sq in.	10
Total temperature, T_e, $^{\circ}F$:	
Nichrome fuel elements	1500
Molybdenum fuel elements	3000 to 3500
NbC-coated graphite fuel elements	3500 to 4000
Tungsten-184 fuel elements	4000 to 4500

The four boost vehicles considered for placing the nuclear stages in orbit are Atlas-Centaur and C-1, C-2, and C-3 versions of Saturn.

The results of the study are summarized as follows:

1. Relatively small, lightweight, high-performance nuclear-rocket powerplants can be obtained by using water as the moderator and Nichrome, molybdenum, coated-graphite, or tungsten-184 as fuel-element materials. Use of tungsten-184 results in highest vehicle performance because the corresponding operating temperature results in the highest specific impulse.

2. For thrust levels below 10,000 pounds, reactor weights will be less than 750 pounds. The corresponding powerplant weights will be under 1200 pounds.

3. Large increases in thrust with the same reactor weight can be obtained by increasing either the dynamic head or the pressure level. Experimental data are needed to determine practical limits of dynamic head.

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4. An average concentration of no higher than 15 percent by volume of uranium dioxide in the tungsten-184 fuel elements of the water-moderated reactors is sufficient; higher concentrations yield an insignificant reduction in reactor weight.

5. A tungsten-184 enrichment of 78 percent, which can be produced in a portion of the existing Oak Ridge Gaseous Diffusion Plant without modification and without significantly altering the nation's output of enriched uranium, is satisfactory. Higher enrichments yield marginal gains. Enrichments as low as 58 percent begin to show noticeable effects on reactor weight.

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6. Insulation of the water moderator from the high-temperature fuel-element regions is technically possible with only small weight and unused-volume penalties.

7. Estimates of water-circulation and cooling requirements indicate that the heat-exchanger and water-pump weights will be only small parts of the overall powerplant weight.

8. Use of a water-moderated nuclear rocket with tungsten enriched in W^{184} or molybdenum fuel elements in conjunction with the Atlas-Centaur booster for orbital-launch missions results in residual-load performance superior to that of a comparable all-chemical system. The advantage increases with the difficulty of the mission. The near-optimum thrust level for this application of a water-moderated powerplant is about 3000 pounds.

9. Use of a water-moderated nuclear-rocket with tungsten enriched in W^{184} or molybdenum fuel elements in conjunction with the Saturn C-1 booster for orbital-launch missions results in a residual-load performance superior to that of either the chemical system or the all-graphite nuclear-rocket system. For the most difficult Saturn C-1 mission considered, the water-moderated, W^{184}-enriched-fuel-element powerplant system shows about a 2.5 residual-load advantage over the all-chemical system. Near-optimum thrust level for missions considered with Saturn C-2 booster is about 8000 pounds.

10. When similarly used with the Saturn C-2 booster, the water-moderated, W^{184}-enriched- or molybdenum-fuel-element powerplants show a large advantage over chemical or all-graphite powerplant designs. For the most difficult mission the residual-load advantage for the water-moderated, W^{184}-enriched-fuel-element powerplant is 2.5 to 1 over either the chemical or the all-graphite systems. A thrust of about 10,000 pounds is near the optimum thrust range.

[redacted]

11. Similarly, used in conjunction with the Saturn C-3 booster, the water-moderated powerplants, with either W^{184}-enriched fuel elements or molybdenum elements, show a large advantage over chemical or current all-graphite powerplant designs. For the most difficult C-3 mission, the residual load for the water-moderated, W^{184}-enriched-fuel-element powerplants is 6.5 to 7.5 times that of a chemical system or 2.5 to 3.0 times that of the graphite-moderated nuclear system. The thrust level of 30,000 pounds is near optimum for the missions presented.

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12. Use of coated-graphite fuel elements in conjunction with a water moderator produces performance between that of the tungsten-184 and the molybdenum-fuel-element, water-moderated powerplants.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, October 27, 1961

[redacted]

APPENDIX A

SYMBOLS

A	area, sq ft
B_g^2	geometric buckling of the unreflected reactor, cm^{-2}
$D(u)$	neutron diffusion coefficient, cm
E	neutron energy, ev
F	thrust, lb
g	gravitational constant, ft/sec^2
$h(u' \rightarrow u)$	probability that a neutron of lethargy u' will change its lethargy into du about u after an inelastic collision
I_{vac}	specific impulse in vacuum, lb/(lb/sec)
k_{eff}	reactor static criticality factor
M	Mach number
P	total pressure, lb/sq ft abs
p	static pressure, lb/sq ft abs
Q	reactor power, mw
$Q(u)$	neutron slowing-down density, neutrons/(cu cm)(sec) crossing unit u
q	dynamic head, lb/sq ft
$\dot{q}$	heat flux, Btu/(sq ft)(sec)
R	gas constant, ft-lb/(lb)($^{\circ}F$)
$S(u)$	neutron source in neutrons produced per cu cm per sec per unit u
T	total temperature, $^{\circ}R$
u	lethargy $\equiv \ln (10^7 \text{ ev}/E)$
V	velocity, ft/sec

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Δv impulsive velocity increment, miles/sec

W weight (at Earth's surface), lb

w mass-flow rate, lb/sec

γ ratio of specific heats

$\gamma(u)$ such that $2\xi(u)\gamma(u)$ is the average squared loss in lethargy per collision

$\xi(u)$ average loss in lethargy per collision

ρ density, lb/cu ft

$\Sigma_a(u)$ macroscopic neutron absorption cross section, cm^{-1}

$\Sigma_{es}(u)$ macroscopic neutron elastic scattering cross section, cm^{-1}

$\Sigma_{in}(u)$ macroscopic neutron inelastic scattering cross section, cm^{-1}

$\varphi(u)$ neutron flux, neutrons/(sq cm)(sec) per unit lethargy

Subscripts:

cs control system

e reactor exit

f reactor flow

H_2 through hydrogen

hx heat exchanger

rad radiation

st along strip

wp water pump

APPENDIX B

TUNGSTEN ISOTOPE SEPARATION

S. A. Levin, D. E. Hatch, and E. von Halle of the Union Carbide Nuclear Company have made an extensive study of tungsten-isotope separation that is not yet available in a published report. The chief results of their study are included in this appendix.

Three cases of operation of the diffusion plants at Oak Ridge are considered. Cases I and II consider operation of portions of the Oak Ridge Gaseous Diffusion Plant designated K-306 and K-305 to produce a 1000-pound lot of tungsten enriched in tungsten-184. The K-306 and K-305 sections are the portions of the plant available for tungsten-isotope separation at the present time. Case III is for a higher steady-state production rate to supply larger requirements. Use of a small portion of the K-25 building was considered for this case.

Case I involves the operation of sections K-306 and K-305 without modification to produce a product material with an absorption cross section of 8.9 barns. Table II gives the results for case I.

Case II considers the use of sections K-306 and K-305 with modifications to increase the degree of separation. Product materials could have absorption cross sections of 5.37, 4.35, or 3.99 barns. The total time to produce the first 1000-pound batch of each composition is increased from the case I time to over 4 years because of a large increase in time for design and construction, an increase in time to attain equilibrium, and an increase in required operating time. For the 5.37-barn material, the cost of the first 1000 pounds is approximately 50 percent higher than for case I; each additional 1000 pounds costs about the same as case I and takes 1.33 years. For the 3.99-barn material, the cost of the first 1000 pounds is approximately twice the cost of case I material; each additional 1000 pounds costs about 75 percent more than case I and takes 2.23 years.

Case III considers the use of the K-25 building without modification to produce tungsten isotopes. The operation of the remaining diffusion plants can be adjusted so that partial use of the K-25 building will have relatively little effect on the overall U-235 production rate. The results of case III, listed in table III, are for steady-state operation. The results do not include the startup costs, which are shown in the footnote. If these costs are amortized over a 10-year period, approximately 10 percent would be added to the steady-state costs shown.

Pilot-plant separation tests have been conducted with tungsten hexafluoride. The tests confirmed the separation factor that had been assumed in the calculations. In addition, the fact that tungsten hexafluoride can be physically handled by the existing gaseous-diffusion equipment was verified.

The isotopic composition of the materials available from the three cases considered is given in table IV.

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APPENDIX C

WATER-TO-HYDROGEN HEAT-EXCHANGER ANALYSIS

Calculation of the weight and dimensions of the water-to-hydrogen heat exchanger required to cool the moderator is based on a simplified analysis and a configuration that is arbitrary in many respects. The resulting values are indicative of the magnitudes and general characteristics to be expected in a final design.

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The heat exchanger is assumed to be a counterflow, tube-and-shell arrangement with hydrogen flowing inside the tubes. The tubes are aluminum, 1/64 inch thick, and 0.258-inch outside diameter. The tubes are in equilateral-triangular array with 1/32-inch separation between closest tube surfaces.

The thermodynamic assumptions for the 230-megawatt example case are listed in the following table:

Reactor-exit hydrogen temperature, $^{\circ}R$	4960
Heat-exchanger-inlet hydrogen temp., $^{\circ}R$	180
Heat-exchanger-inlet water temp., $^{\circ}R$	710
Heat-exchanger-exit water temp., $^{\circ}R$	580
Heat-exchanger-exit hydrogen Mach number	0.20
Heat-exchanger minimum tube temp., $^{\circ}R$	492
Heat-exchanger-exit hydrogen pressure, lb/sq in. abs	354
Moderator heating rate/Reactor power	0.07

Computed values of hydrogen flow rate and heat-exchanger-exit hydrogen temperature are 12.3 pounds per second and 580° R, respectively. The restriction on minimum tube temperature, imposed to prevent freezing of the water, is used to find satisfactory combinations of tube diameter and exit water temperature. The particular combination selected is one that gives a tube length compatible with reactor core length.

[redacted]

The resulting heat exchanger has the following characteristics:

Number of tubes	428
Length of tubes, ft	4.6
Total water-side surface area, sq ft	133.3
Weight of tubes, lb	28.3
Weight of water, lb	16.7
Total heat-exchanger weight, lb	57.5
Heat-exchanger frontal area, sq ft	0.43

The heat-exchanger weight is assumed to be greater than the combined weights of tubes and water by 28 percent to account for headers, baffles, spacers, and other structure. The frontal area is twice the inlet frontal area because of the assumption that the tubes will be doubled back in order to be compatible with a core length of about 2 feet.

Pressure drops on hydrogen and water sides are 29 and 76 pounds per square inch, respectively. Total water flow rate is 118 pounds per second.

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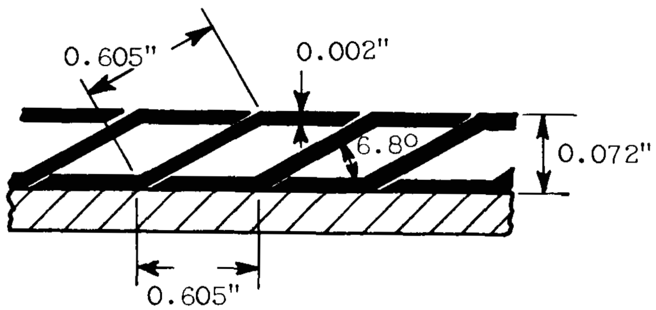
APPENDIX D

SHINGLE-TYPE INSULATION ANALYSIS

Calculation of the effective thermal conductivity of "tungsten-shingle" insulation is made in accordance with the methods described by Dugger, Billig, and Avery (ref. 5). The analysis is shown to approximate closely experimental measurement (ref. 5). A similar geometry has been adopted for the water-moderated reactor application to ensure applicability of analytical methods.

The assumed geometry is shown schematically in the accompanying sketch. The spaces between shingles are open at the ends so that static



pressure will be equalized along the reactor axial dimension. Tabs would probably be provided on the downstream edges of the shingles to increase structural integrity. The angle between the shingles and the base has been retained from the geometry in reference 5. The assumed structure has an equivalent tungsten thickness of 0.006 inch and a weight of 0.6 pound per square foot.

The effective thermal conductivity of such a structure depends upon the overall temperature differential. The most severe condition will be at reactor exit, where the surfaces that "see" the fuel elements will be at approximately 4000° R and the water temperature will be lowest. A temperature of 800° R is assumed for the shingle side of the aluminum wall. The resulting water-side heat flux is found to be acceptable. Using the equations of reference 5 and appropriate physical properties for tungsten and hydrogen, the three heat-flux components that make up the total are evaluated:

$$\dot{q}_{st} \text{ (along shingles)} = 4.1 \text{ Btu/(sec)(sq ft)}$$

$$\dot{q}_{H_2} \text{ (across gap)} = 47.2 \text{ Btu/(sec)(sq ft)}$$

$$\dot{q}_{rad} \text{ (between shingles)} = 5.2 \text{ Btu/(sec)(sq ft)}$$

All fluxes are based on a square foot of wall area.

[redacted]

In computing the interchange factor in the radiation equation, emissivities of 0.282 and 0.048 are assumed for tungsten at 4000° and 800° R, respectively. Although these values may prove to be low, the results are not sensitive to this assumption. The thermal conductivities of hydrogen and tungsten at 2400° R are 8.6×10^{-5} and 0.0193 Btu/(sec)(ft)($^{\circ}$R), respectively.

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Thus, the effective thermal conductivity at reactor exit is 1.06×10^{-4} Btu/(sec)(ft)($^{\circ}$R) or 0.381 Btu/(hr)(ft)($^{\circ}$R). Over the length of the reactor the average value will be somewhat less than this maximum value because of the smaller contribution due to radiation and because of the lower temperature of the hydrogen in contact with the shingles.

In the 230-megawatt reactor used as an example in the body of the report, there would be 21.1 square feet of insulated surface. The average temperature difference across the 0.072-inch thickness of shingles would be about 1600° F. Using an average effective thermal conductivity of 1×10^{-4}, the rate of heat transfer to the moderator will be 563 Btu per second or 0.59 megawatt. Thus, less than 0.3 percent of total reactor power is transferred through the insulation into the water. This represents a small fraction of the heat that is generated in the water due to neutron and gamma heating, which is about 6.5 percent of the total reactor power.

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TABLE I. - WATER-MODERATED, TUNGSTEN-184 NUCLEAR-ROCKET

POWERPLANT CHARACTERISTICS

Reactor thrust, F, lb	3,000	10,000	25,000
Reactor power, Q, mw	70	230	560
Hydrogen flow rate, w, lb/sec	3.4	11.3	28.2
Reactor-exit gas temperature, T_e, ^{o}F	4500	4500	4500
Reactor-exit total pressure, P_e, lb/sq in. abs	300	300	300
Reactor-exit dynamic head, q_e, lb/sq in.	10	10	10
Reactor flow area, A_f, sq in.	14.7	48.9	122
Reactor void area, sq in.	17.6	58.6	147
Reactor diameter, in.	24.8	25.6	29.2
Reactor length, in.	19.9	20.5	23.3
Flow-passage hydraulic diameter, in.	0.066	0.068	0.078
Volume ratio of UO_2 to total W plus UO_2	0.15	0.15	0.15
Static criticality factor, k_{eff}	1.05	1.05	1.05
Weight breakdown, lb:			
Moderator water	330	345	480
Tungsten	98	325	817
Uranium-235 dioxide	9	30	75
Heat exchanger (wet)	17	58	140
Pressure shell	67	73	90
Nozzle	40	70	140
Waterpump and drive	40	40	56
Hydrogen turbopump	40	40	40
Reactor control system	100	100	100
Total weight, lb	741	1081	1938

[redacted]

TABLE II. - TUNGSTEN-ISOTOPE SEPARATION IN K-306 AND K-305 SECTIONS OF OAK RIDGE GASEOUS DIFFUSION PLANT

[Operation of K-306 and K-305 sections without modification to produce material with a cross section of 8.9 barns (case I).]

Cost and time for initial 1000-pound lot		
	Cost with depreciation charge, millions of dollars	Cost without depreciation charge, millions of dollars
Startup	1.900	1.800
Feed	.600	.600
Operation	5.800	1.900
Power	1.600	1.600
Total cost	9.900	5.900
Time, months:		
Design and construction	3.0	
Equilibrium	2.5	
Operating	10.7	
Total time	16.2	
Cost and time for additional 1000-pound lots		
	Cost with depreciation charge, millions of dollars	Cost without depreciation charge, millions of dollars
Feed	0.570	0.570
Operation	4.700	1.500
Power	1.300	1.300
Total cost	6.570	3.370
Time, months	10.7	

[redacted]

TABLE III. - TUNGSTEN-ISOTOPE SEPARATION IN K-25 BUILDING

[Case III.]

Cross section, barns	7.18	5.80	4.52
Annual feed rate, lb	89,600	89,600	89,600
Annual production rate, lb	17,900	13,400	8,950
Preproduction operating time, days	206	268	343
Annual operating costs, millions of dollars	12.887	12.887	12.887
Annual depreciation costs, millions of dollars	10.000	10.000	10.000
Annual feed costs, millions of dollars	.448	.448	.448
[a]Cost of product with depreciation, $/lb	1300	1740	2610
[a]Cost of product without depreciation, $/lb	750	990	1490

[a]The cost per pound listed does not include startup costs, which are $4,200,000 and $3,900,000 with and without depreciation, respectively.

[redacted]

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TABLE IV. - ISOTOPIC COMPOSITION AND THERMAL NEUTRON CROSS SECTIONS

OF TUNGSTEN FEED AND PRODUCT STREAMS

	Gross section, barns	Isotopic concentration, percent				
		W-180	W-182	W-183	W-184	W-186
Feed (natural tungsten)	17.51	0.14	26.41	14.41	30.62	28.56
Product of case I	8.90	0.03	10.0	20.0	60.0	10.0
Products of case II	5.37 4.35 3.99	10^{-4} 10^{-6} 10^{-6}	4.3 .7 1.5	19.4 11.8 16.7	73.8 84.0 81.1	2.6 3.5 .6
Products of case III	7.18 5.80 4.52	10^{-3} 10^{-4} 10^{-4}	13.9 7.8 3.4	27.6 23.8 17.1	57.9 67.6 78.4	0.6 .8 1.1

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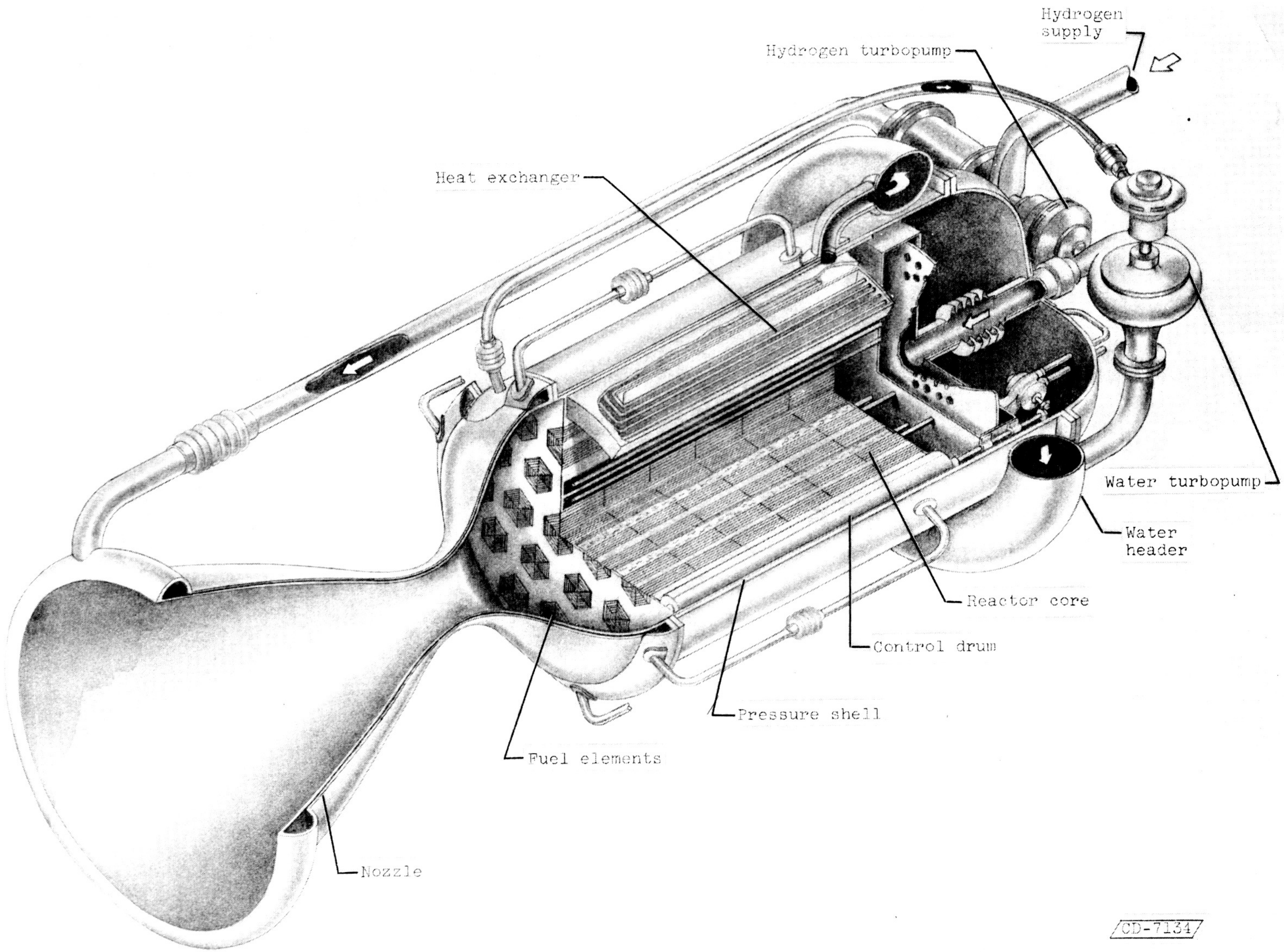

Figure 1. - Schematic drawing of 230-megawatt water-moderated nuclear-rocket propulsion system using tungsten-184 fuel elements.

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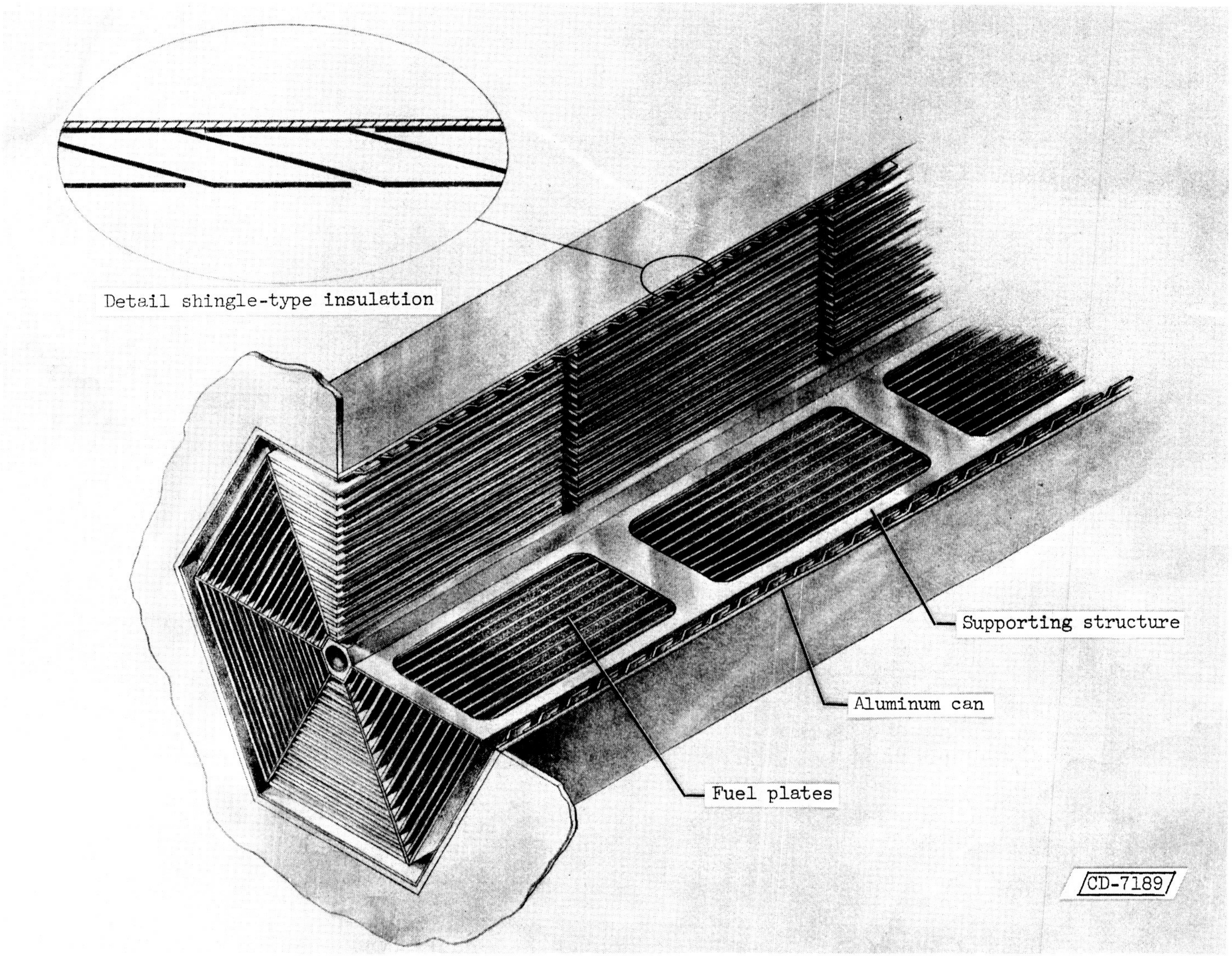

Figure 2. - Schematic drawing of tungsten-184 fuel element for water-moderated nuclear-rocket propulsion system.

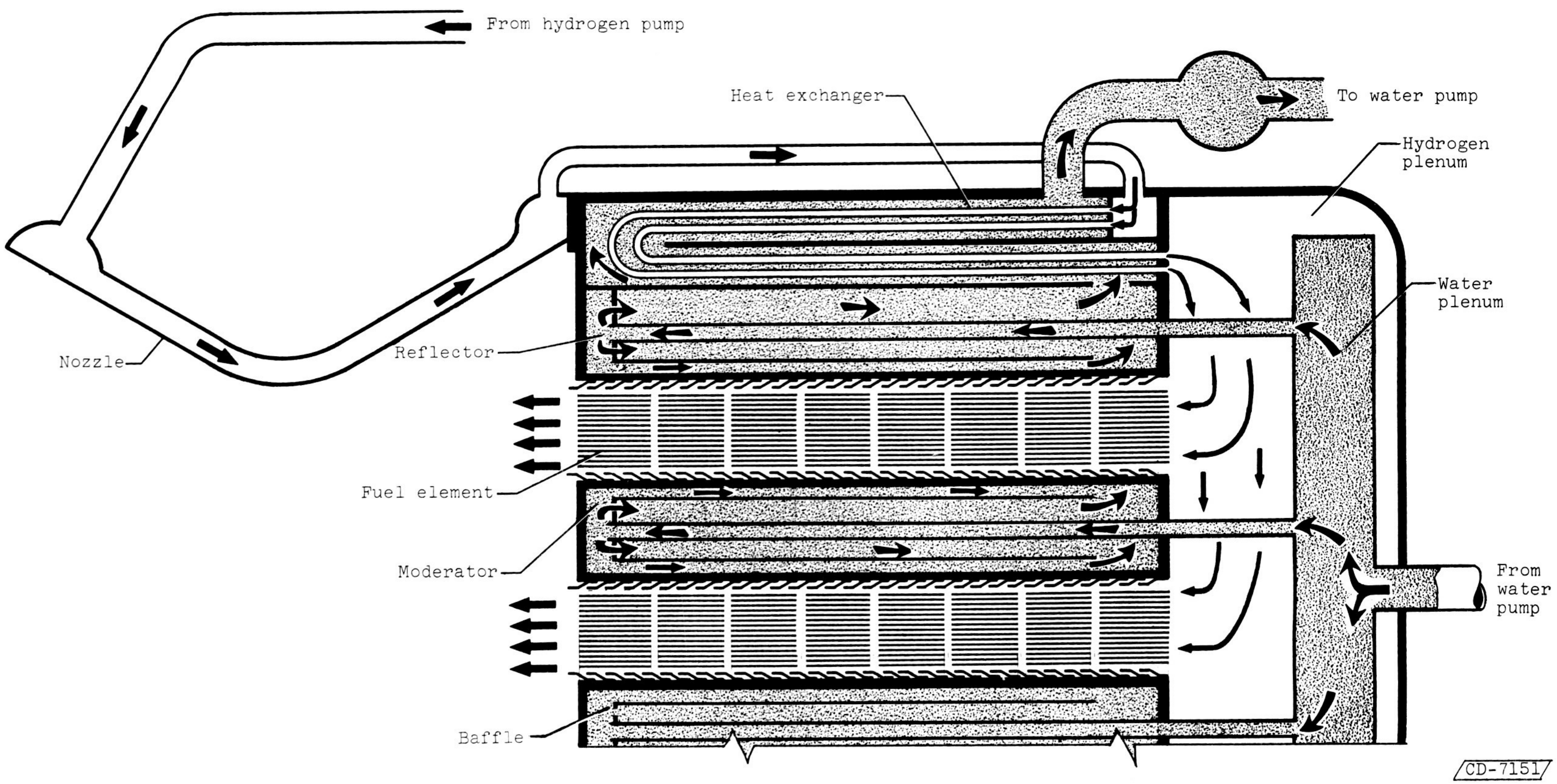

Figure 3. - Schematic flow diagram for water-moderated nuclear rocket.

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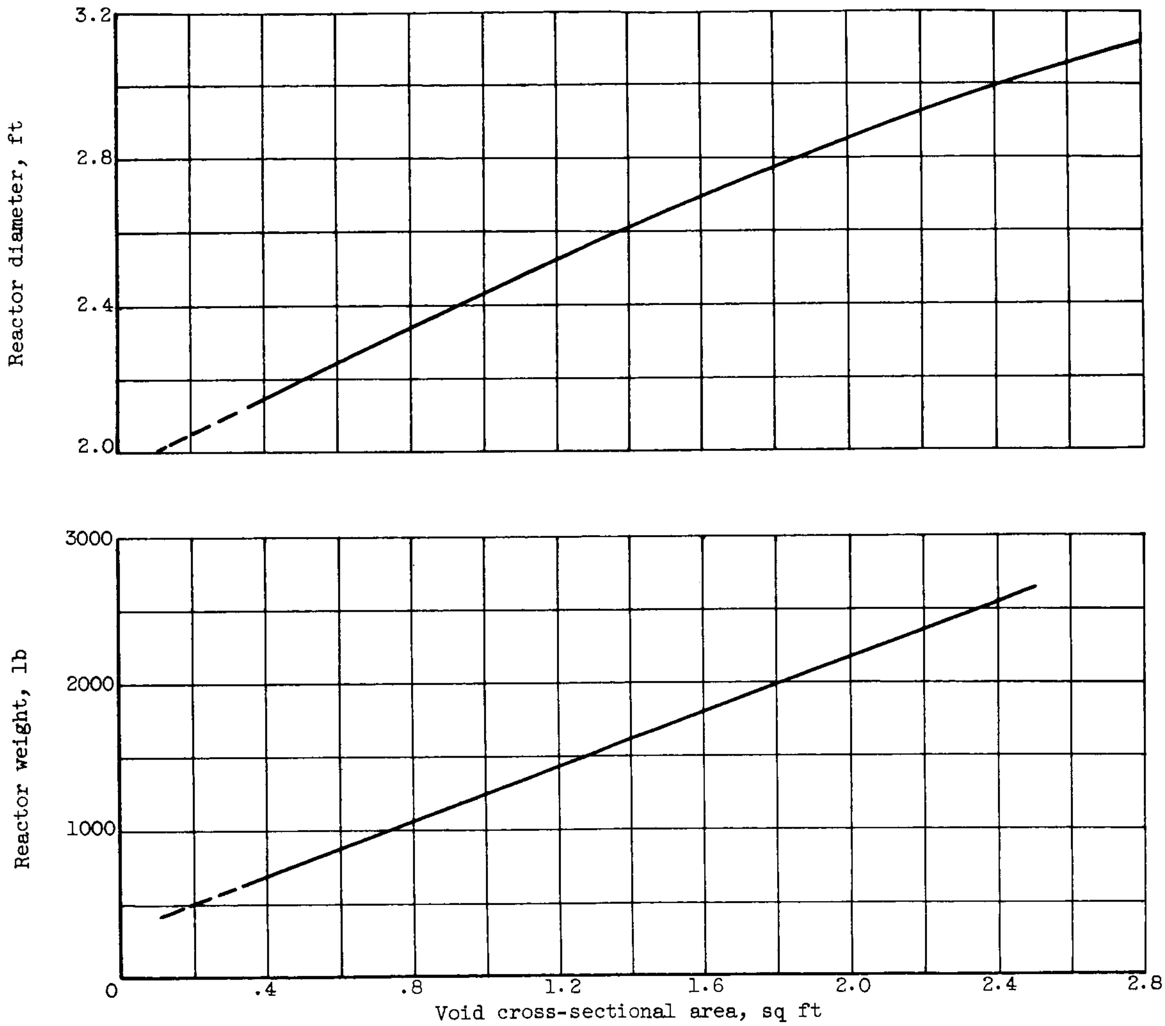

Figure 4. - Weight and diameter of bare water-moderated reactor cores using 0.78 tungsten-184 enriched fuel elements. Volume fraction of UO_2 in fuel elements, 0.15; optimum reactor core length (reactor length-to-diameter ratio $\approx$ 0.8); static criticality factor, 1.05; weight of tungsten per unit void cross-sectional area, 800 pounds per square foot.

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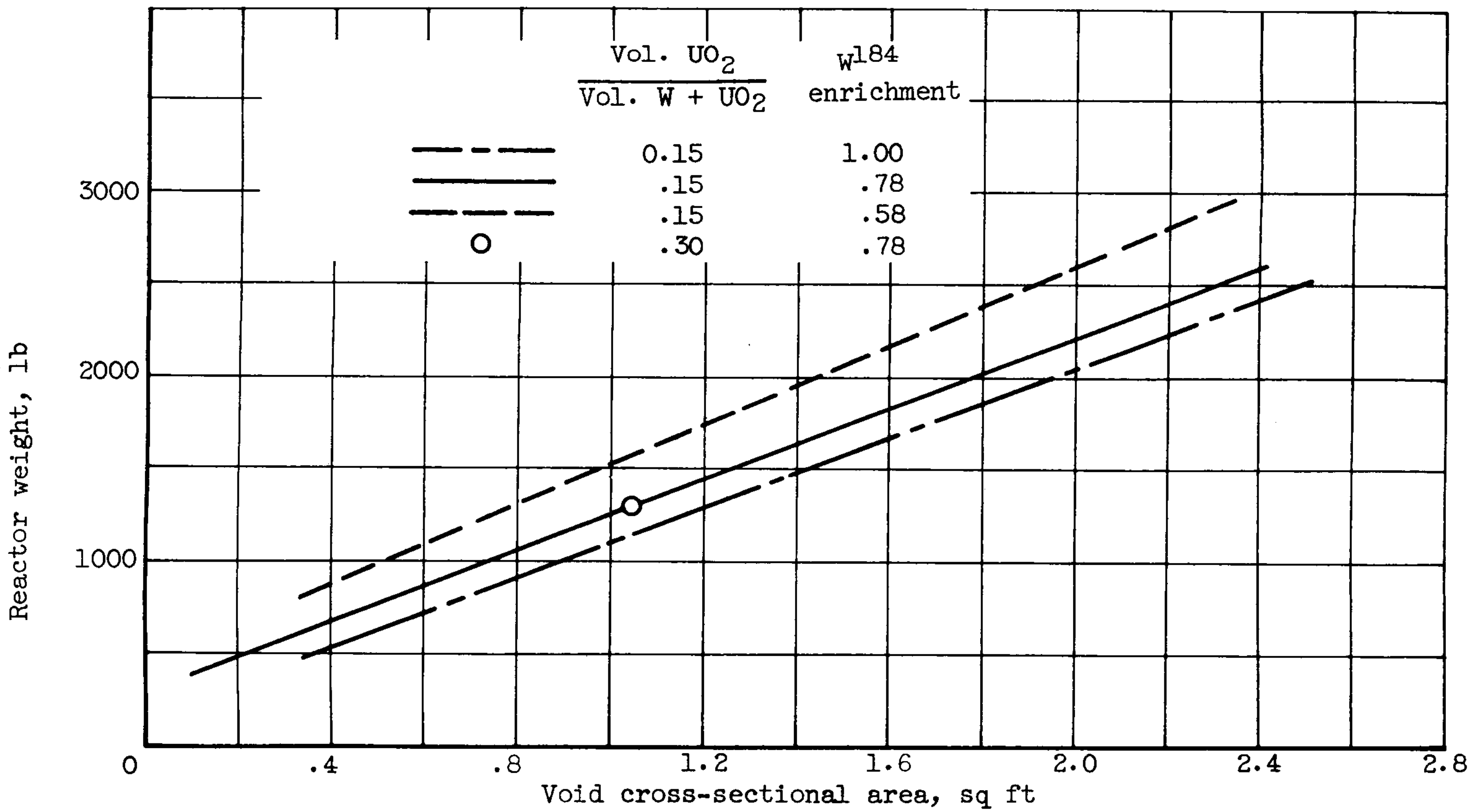

Figure 5. - Effect of UO_2 volume fraction and enrichment of tungsten-184 on bare water-moderated reactor core weight. Optimum core length; static criticality factor, 1.05; weight of tungsten per unit void cross-sectional area, 800 pounds per square foot.

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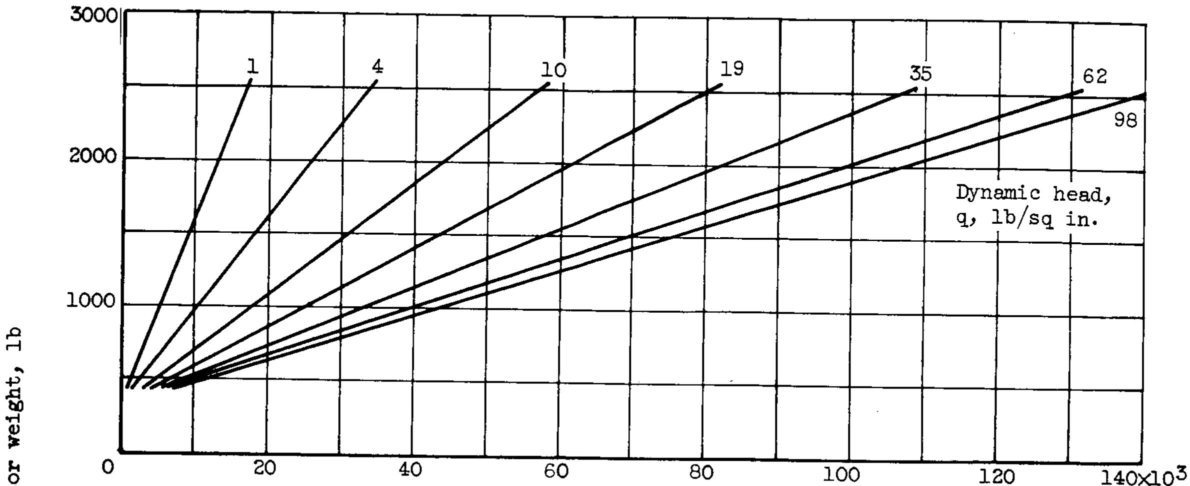
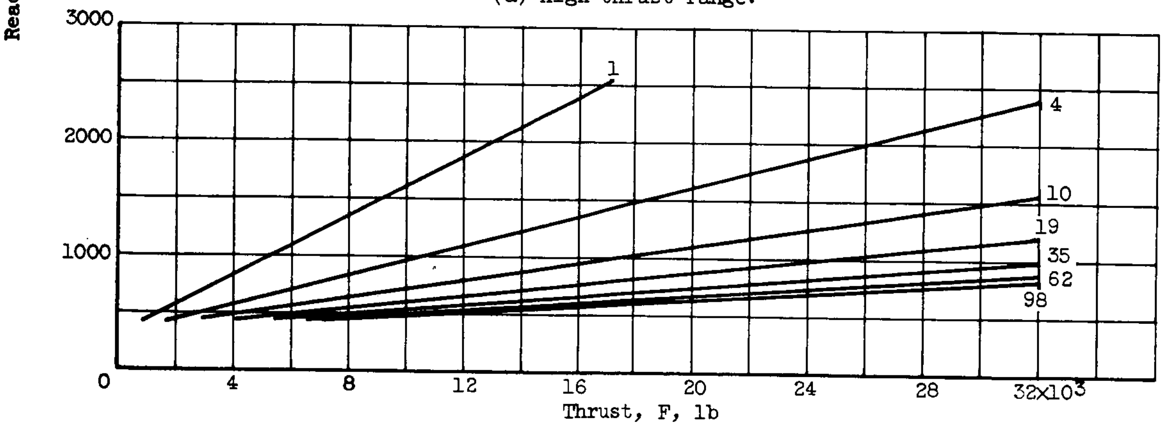


(a) High thrust range.



(b) Low thrust range.

Figure 6. - **Thrust of water-moderated reactor cores using 0.78 tungsten-184 enriched fuel elements. Volume fraction of UO_2 in fuel elements, 0.15; optimum reactor core length; static criticality factor, 1.05; ratio of void cross-sectional area to flow area, 1.20; reactor-exit pressure, 300 pounds per square inch absolute; reactor-exit temperature, 4000° to 4500° F; weight of tungsten per unit void cross-sectional area, 800 pounds per square foot.**

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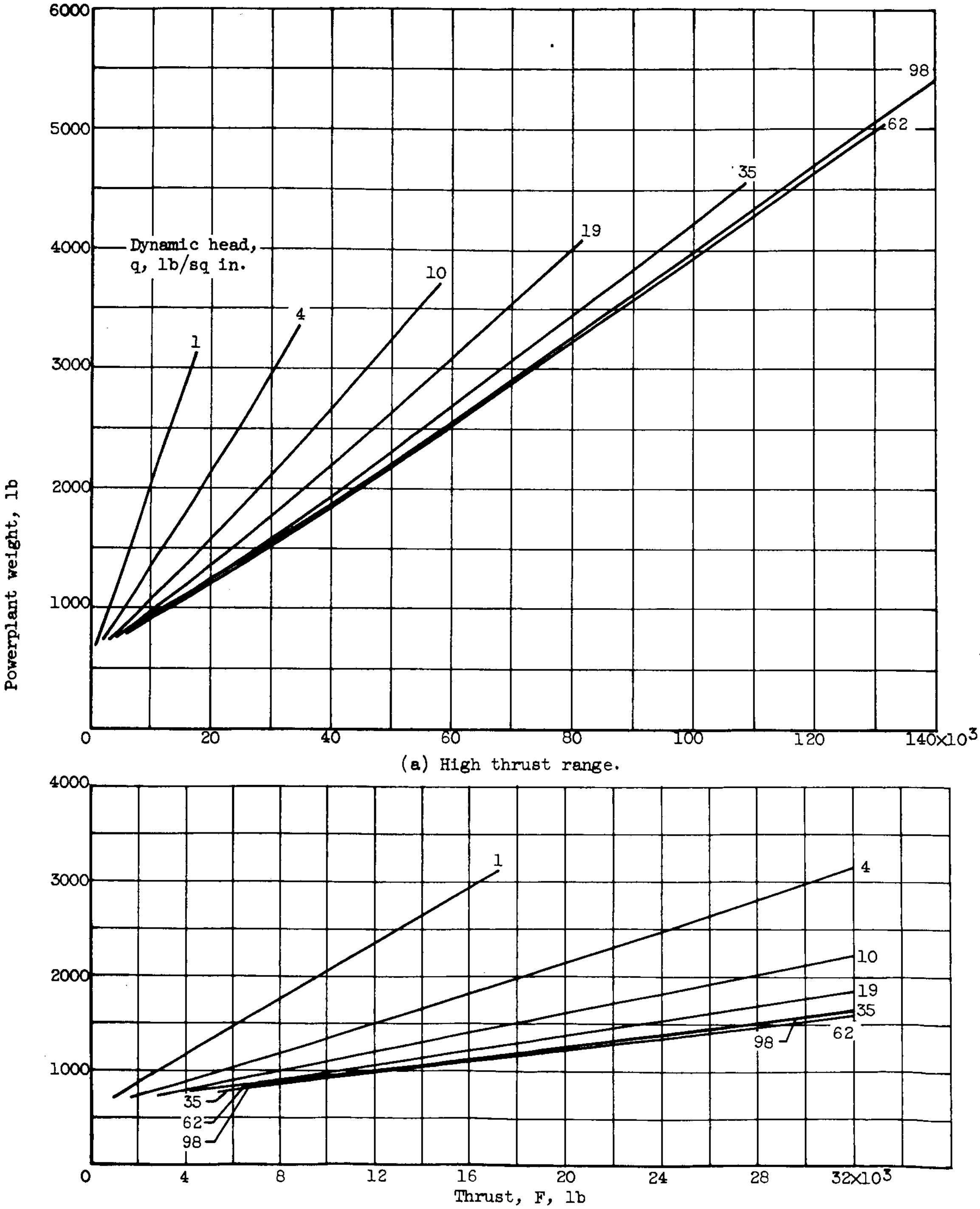

(b) Low thrust range.

Figure 7. - Weight of water-moderated, tungsten-184 nuclear-rocket powerplants. Tungsten-184 enrichment, 0.78; volume fraction of UO_2 in fuel elements, 0.15; reactor-exit pressure, 300 pounds per square inch absolute; reactor-exit temperature, 4000° to 4500° F; weight of tungsten per unit void cross-sectional area, 800 pounds per square foot.

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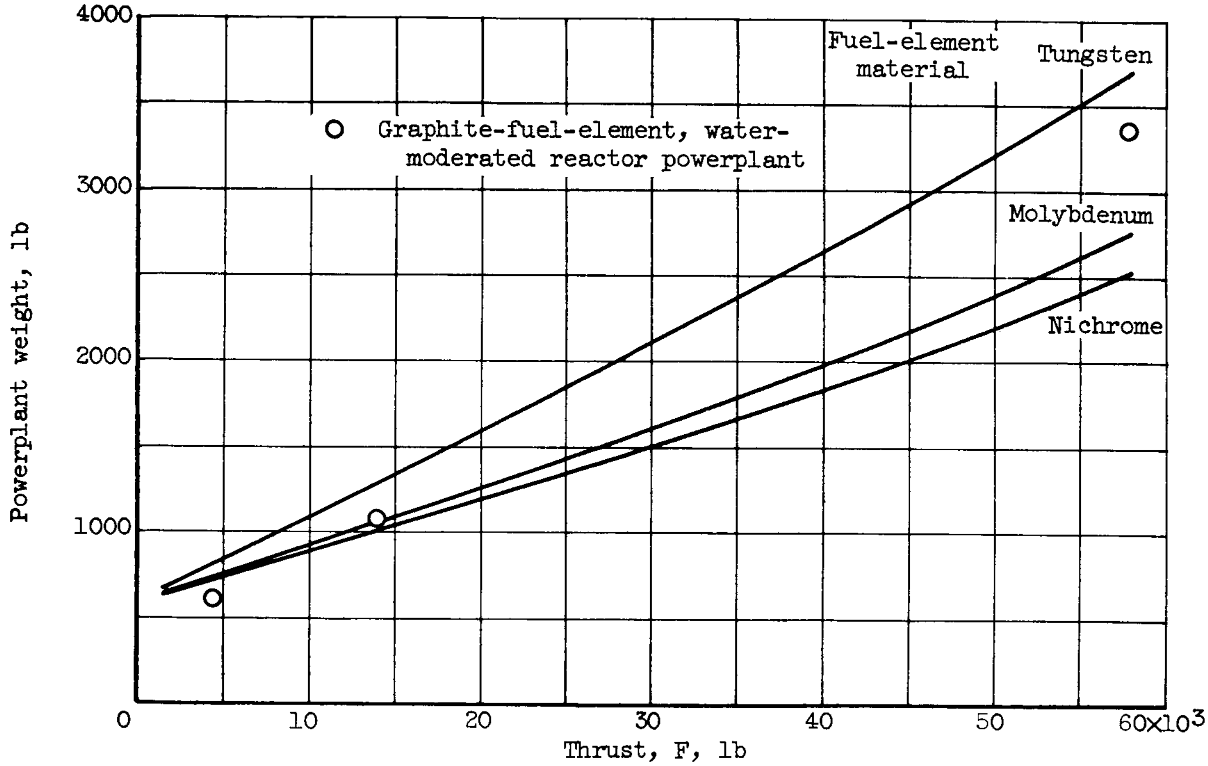

Figure 8. - Weight of water-moderated nuclear-rocket powerplants using Nichrome, molybdenum, and 0.78 tungsten-184 as fuel elements. Volume fraction of UO_2 in fuel elements, 0.15; reactor-exit pressure, 300 pounds per square inch absolute; weight of tungsten per unit void cross-sectional area, 800 pounds per square foot; volume of molybdenum and Nichrome equal to that of tungsten.

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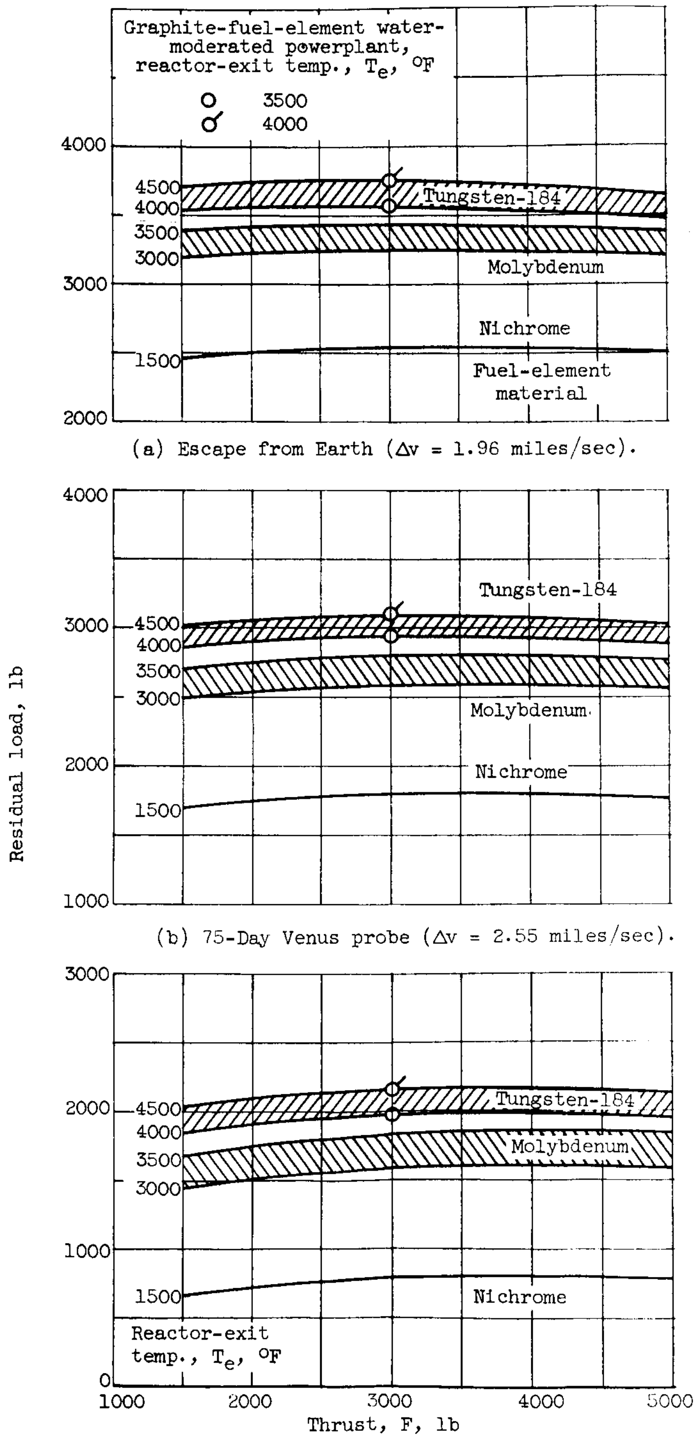

(a) Escape from Earth (Δv = 1.96 miles/sec).

(b) 75-Day Venus probe (Δv = 2.55 miles/sec).

(c) 100-Day Mars probe (Δv = 3.60 miles/sec).

Figure 9. - Performance of orbital-launch, water-moderated nuclear rockets in missions with the Atlas-Centaur as booster. Orbit altitude, 300 statute miles; initial weight in orbit, 7600 pounds.

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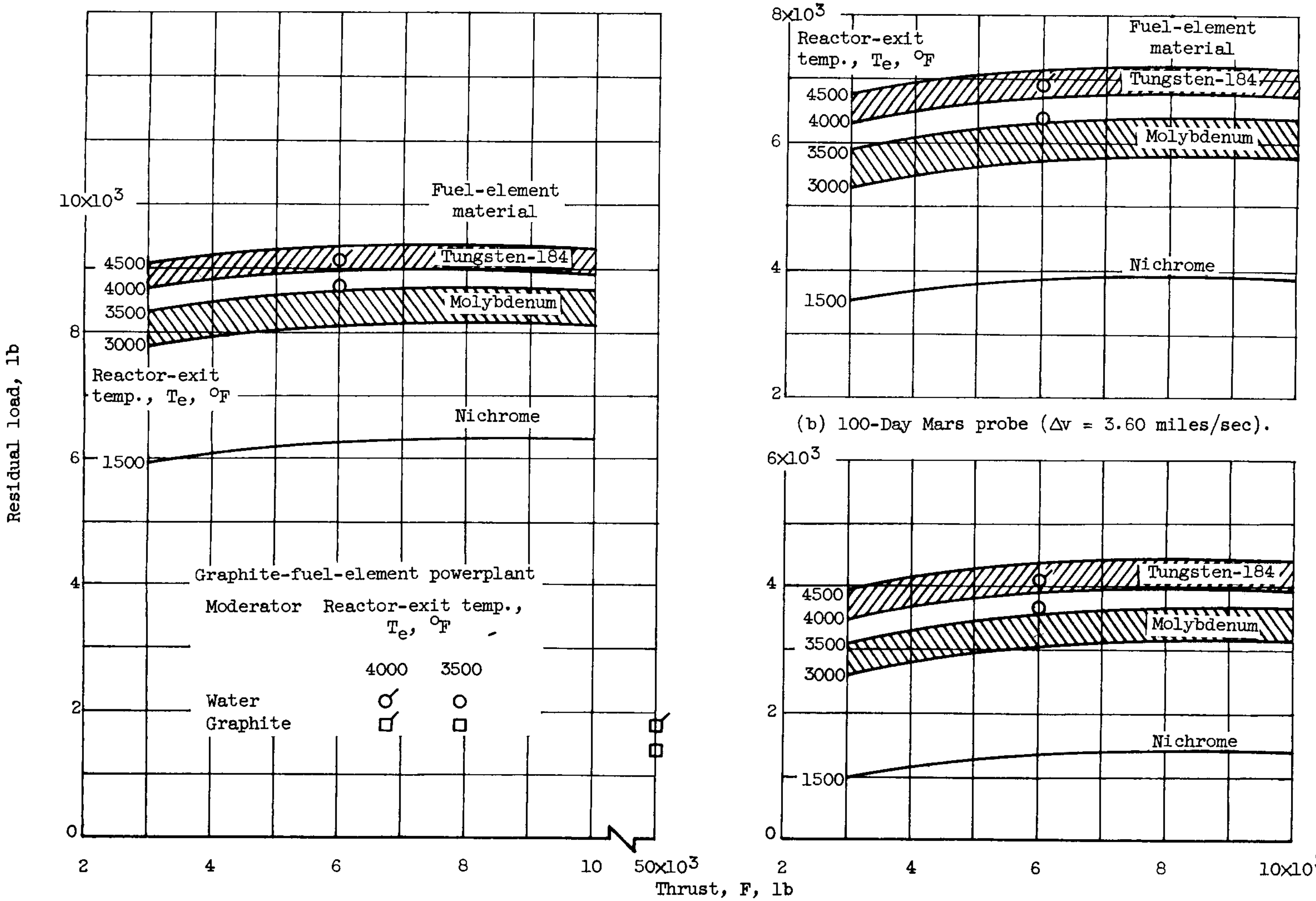

(a) 75-Day Venus probe (Δv = 2.55 miles/sec).

(b) 100-Day Mars probe (Δv = 3.60 miles/sec).

(c) 413-Day Jupiter probe (Δv = 5.27 miles/sec).

Figure 10. - Performance of orbital-launch, water-moderated nuclear rockets in missions with Saturn C-1 as booster. Orbit altitude, 300 statute miles; initial weight in orbit, 18,000 pounds.

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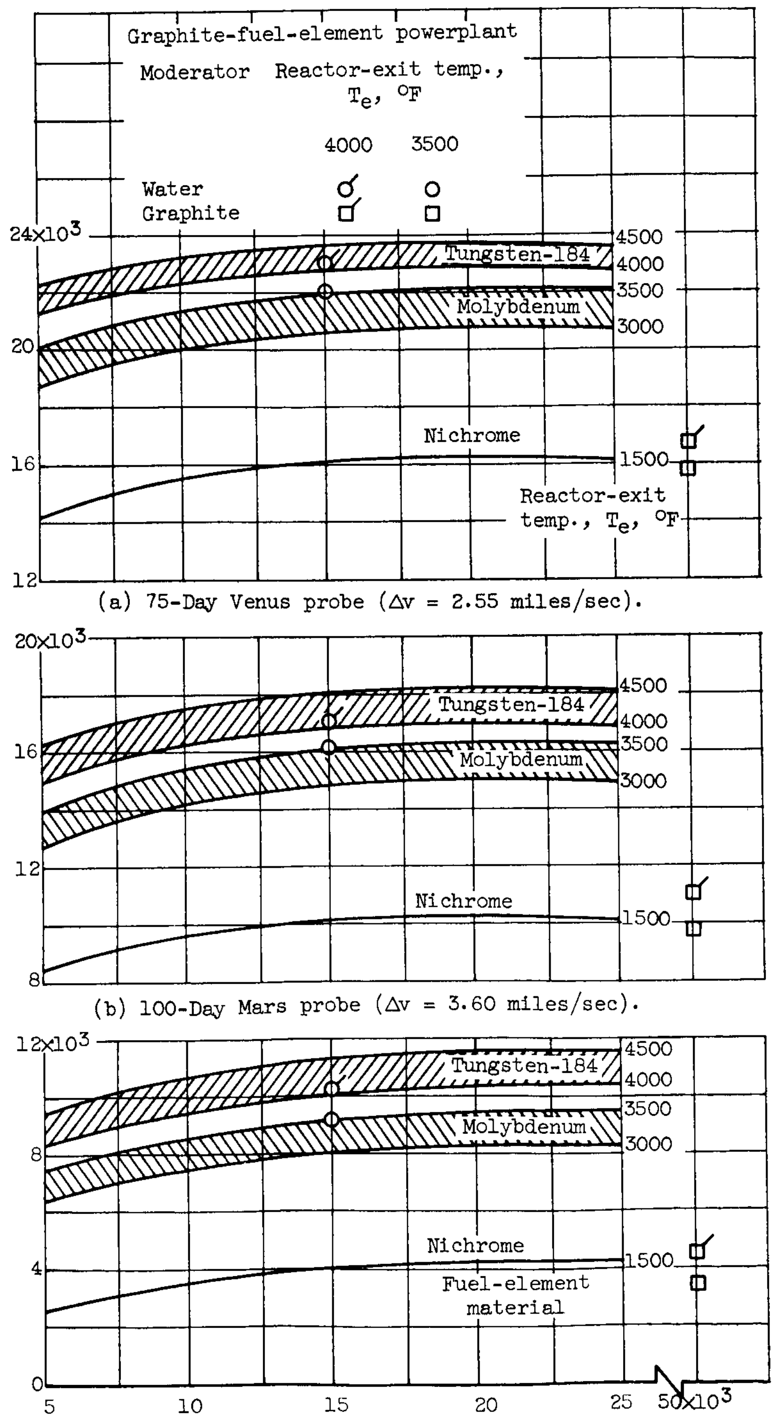

(a) 75-Day Venus probe (Δv = 2.55 miles/sec).

(b) 100-Day Mars probe (Δv = 3.60 miles/sec).

(c) 413-Day Jupiter probe (Δv = 5.27 miles/sec).

Figure 11. - Performance of orbital-launch, water-moderated nuclear rockets in missions with Saturn C-2 as booster. Orbit altitude, 300 statute miles; initial weight in orbit, 42,700 pounds.

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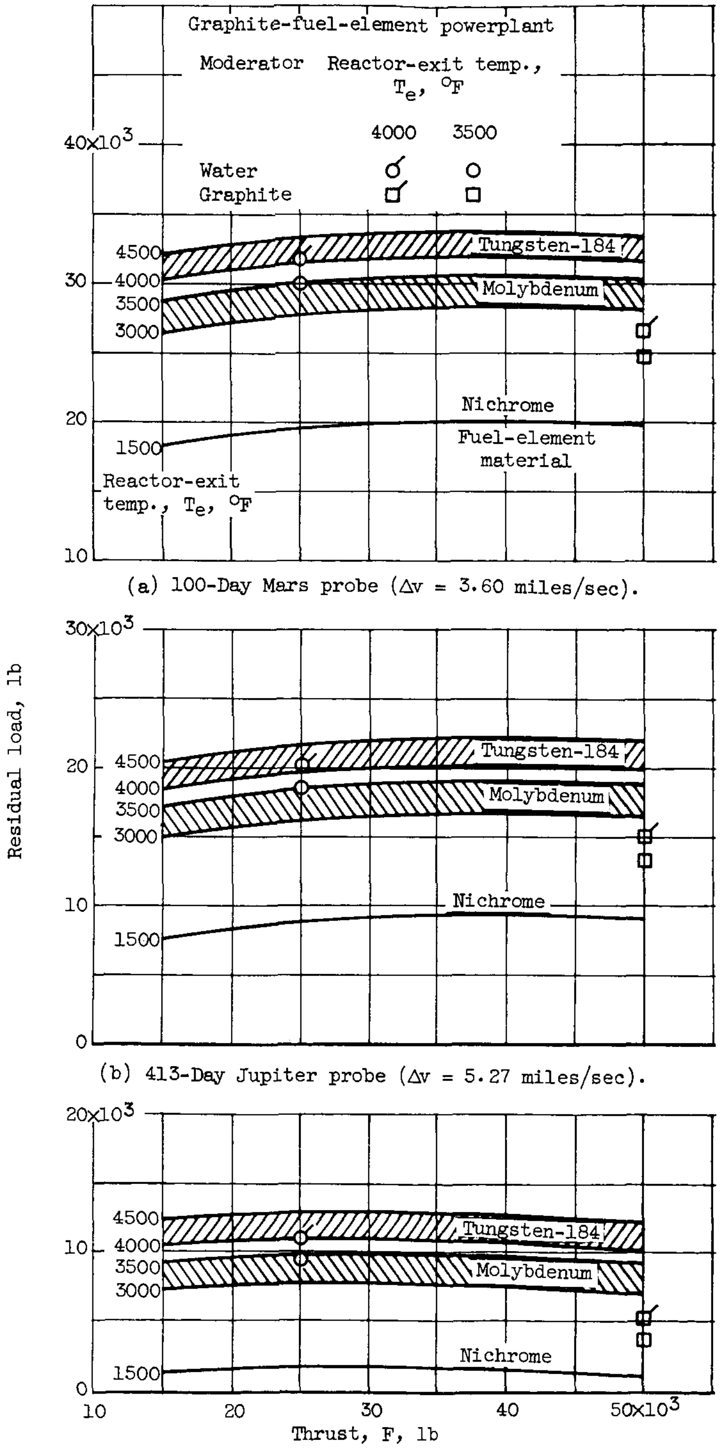

(a) 100-Day Mars probe (Δv = 3.60 miles/sec).

(b) 413-Day Jupiter probe (Δv = 5.27 miles/sec).

(c) 125-Day trip to Mars orbit (Δv = 7.38 miles/sec).

Figure 12. - Performance of water-moderated nuclear rockets in missions with Saturn C-3 as booster. Orbit altitude, 300 statute miles; initial weight in orbit, 77,000 pounds.

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WATER-MODERATED NUCLEAR ROCKETS. (REVISED)
Frank E. Rom, Paul G. Johnson, and Robert E. Hyland.
December 1961. 45p. diagrs., tabs. (NASA TM X-482)

Nuclear-rocket powerplants with water-moderated reactors are relatively small and lightweight and can be used for orbital-launch stages that are boosted into orbit with vehicles now being developed by NASA (Atlas-Centaur, Saturn). Performance of such stages is computed for orbital-launch missions and gross weights compatible with the specified boosters. Use of W^{184}, coated-graphite, or Mo fuel elements in these reactors would yield performance several times superior to that expected of the best all-chemical system. Nichrome fuel elements are expected to yield performance comparable to that of an optimum chemical system. Of these four fuel-element materials, W^{184} offers the greatest overall performance potential.

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